SECTION 1. EXECUTIVE DIGEST

1.1 BACKGROUND

The piezoelectric effect was discovered by brothers, Pierre and Jacques Curie in 1883 when they were 24 and 21 years old, respectively. This physical phenomenon observed that certain crystals produced an electrical charge when subjected to mechanical force. A 1935 ballistic pressure sensor used by Oerlikon Bührle of Switzerland was described by Dr. Werner Gohlke in his book published in 1959 on Piezoelectric Technology. Early piezoelectric sensors were coupled with an Electrometer Amplifier and were sufficiently sensitive that they required a measurement of capacitance each time a cable was changed.

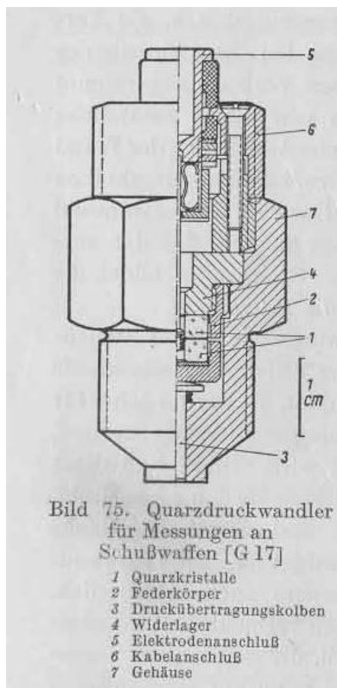


Figure 1. Piezoelectric Transducer used by Oerlikon Bührle, circa 1935. This quartz based gage required disassembly and cleaning between rounds. Drawing provided by Paul Engeler of Kistler Instrumente AG, Winterthur Switzerland.

Development of charge amplifiers in the 1950s permitted further exploitation of the effect. Since that time a variety of ballistic pressure sensors have been designed and developed ranging from commercially available quartz sensors to the original APG Tourmaline sensor (using an exposed crystal) and its antecedent the US Army Model E30MA (employing an encapsulated crystal).

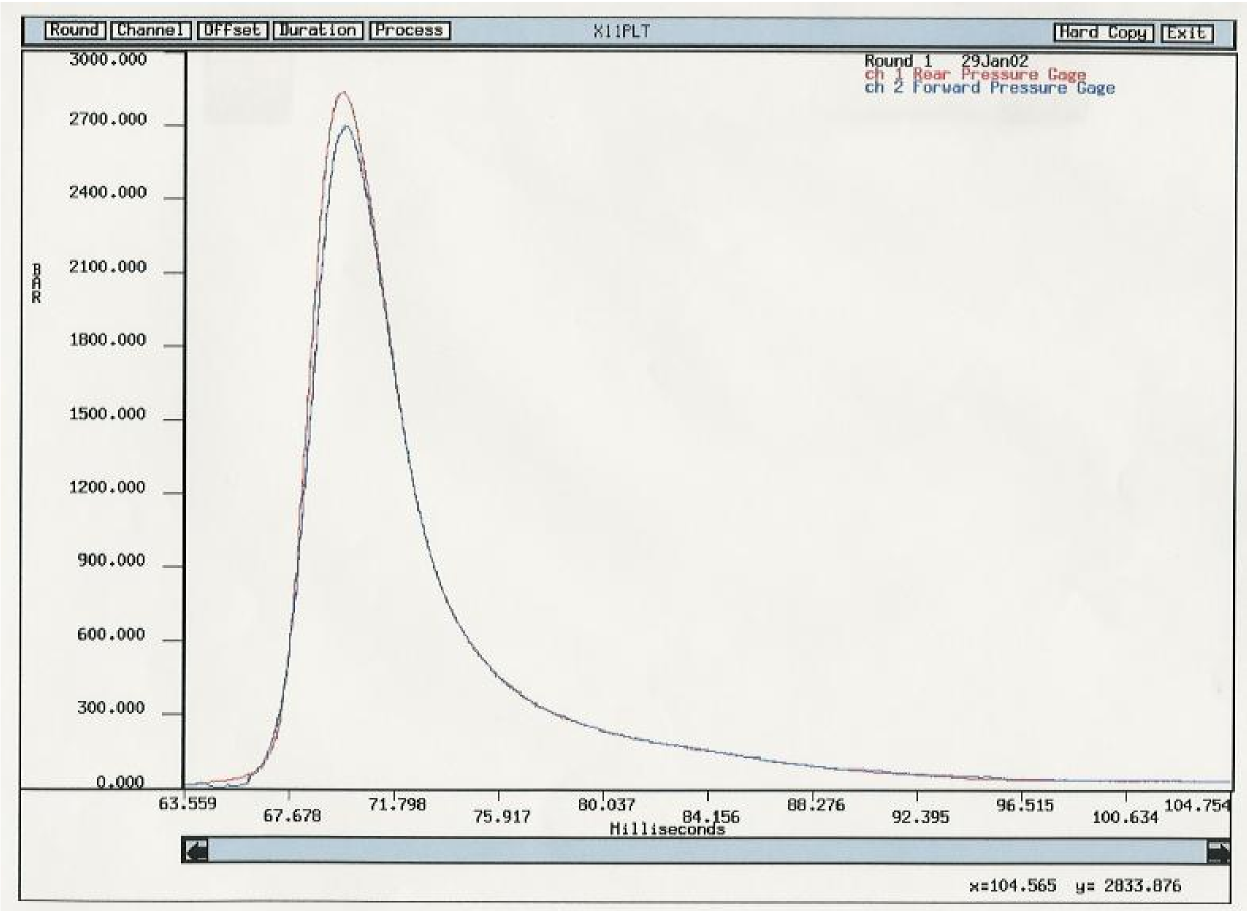
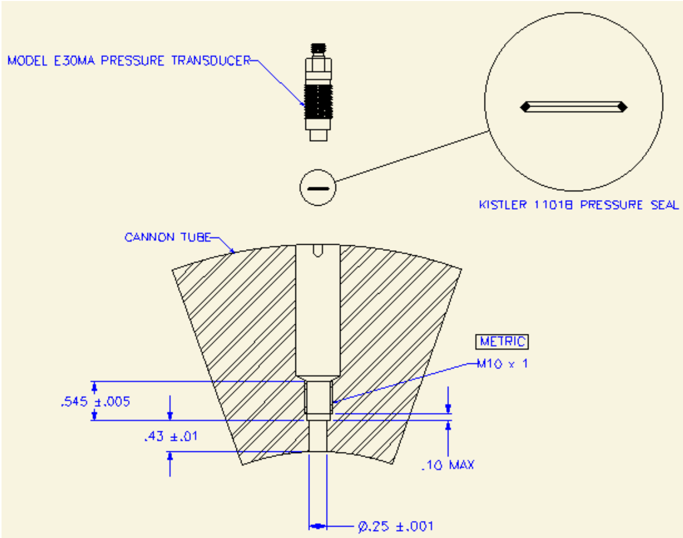


Figure 2. Typical chamber pressure traces for a cannon instrumented with one forward chamber sensor and one rear chamber pressure sensor. The rear peak pressure should always be slightly higher than the forward peak pressure and the pressure curves should nearly overly each other.



Figures 3a and 3b. The US Army Model E30MA ballistic pressure transducer is the standard for measuring chamber pressure in direct fire cannon and ammunition for the US Army.

Presently, the accuracy for chamber pressure measurement at Aberdeen Test Center is 1% and is typically achieved better than 99.5% of the time. Occasionally anomalies in measurement are observed that result in less than stated accuracy. This report attempts to address some of the discrepancies that may be observed in the course of chamber pressure measurement and offer solutions or explanations that may lead to other preventative measures.

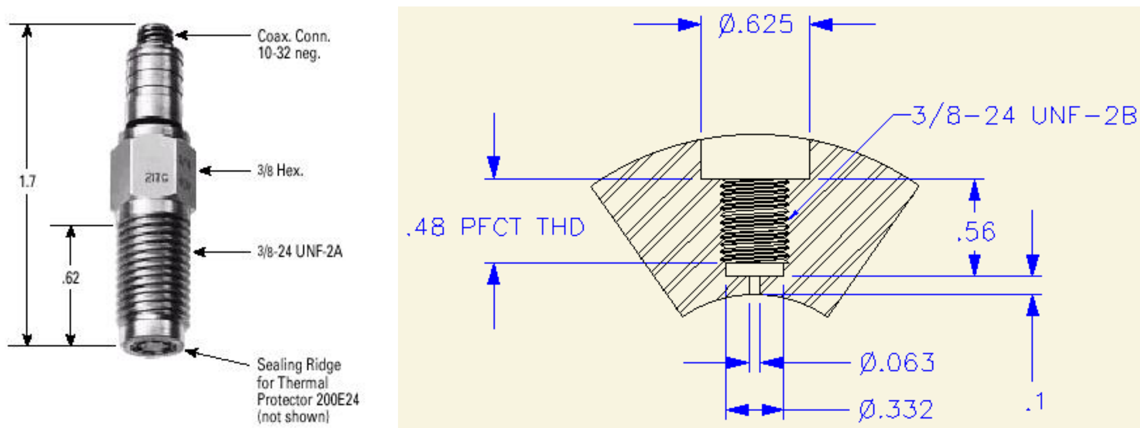
Devices for Measuring	Measurement Accuracy
Range	0 - 1000 MPa
Insulation resistance	≥5 x 10^{13} Ohm (desired)
	≥ 10^{12} Ohm (required)
Natural frequency	≥150 kHz
Linearity	±1% of full scale output (FSO)
Shock resistance	≥100,000 m/sec^2
Calibration factor repeatability	
cycle to cycle	±0.5%
calibration to calibration	±2%
lifetime	±5%
Operating temperature	-50°C - +200°C

Table 1. Requirements for Pressure Transducers from ITOP 3-2-810.

1.2 DISCUSSION

Case 1. Helmholtz Resonance.

During Mann Barrel acceptance testing in April 2002 a Kistler Model 617 was designated for use by the customer based upon previous experience. The cartridge case was drilled with a Ø0.125 hole permitting the transducer to be exposed to propellant gas pressure. Cartridge case alignment was essential to obtaining good pressure data.



Figures 4a and 4b. Kistler Model 217C Ballistic Pressure Transducer, dimensionally identical to Kistler Model 617C, and the recommended pressure port.

Despite use of the recommended pressure port, Helmholtz resonance was present which forced the ballistics technician to subjectively estimate the actual peak pressure.

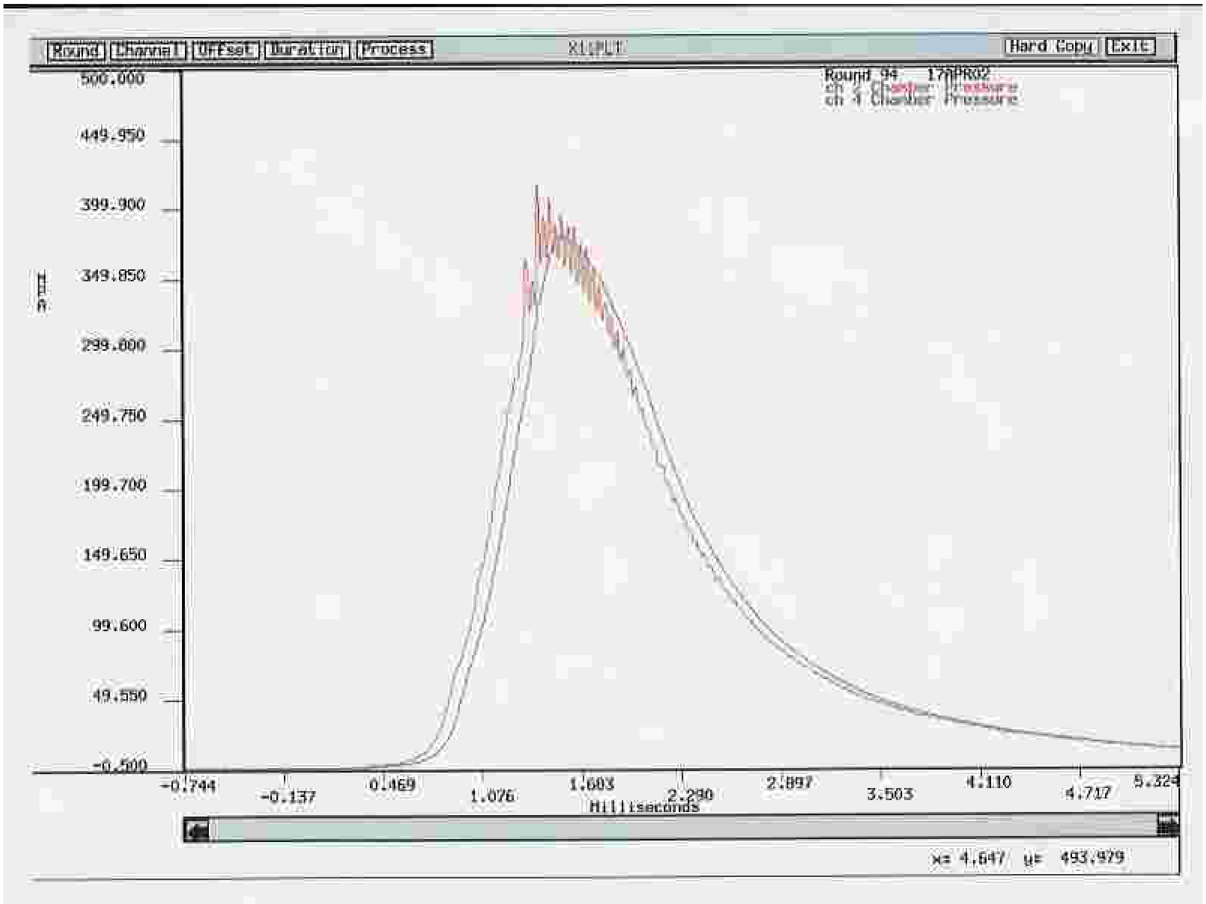


Figure 5. Pressure trace from unfiltered charge amplifier output showing 20 KHz Helmholtz Resonance or "ringing" beginning just prior to peak pressure. Successive attempts at filtering out the 20 KHz "ringing" led to an optimal level of filtering at 5 KHz. This figure shows the original pressure trace side by side with the filtered pressure trace.

Filtering was tried at four different levels (20 KHz, 10 KHz, 5 KHz, and 1 KHz) to reduce the effect of "ringing" until an optimum filter level was found at 5 KHz. All subsequent testing was accomplished using a 5 KHz filtered signal to report peak chamber pressure. Based on the success with this approach to eliminating Helmholtz Resonance, a 5 KHz filter will be used in subsequent 25mm testing with the Kistler Model 617 Transducer.

Case 2. Cable Whip Induced Signal Breakup.

During testing of a 90mm Cannon in February 2002 a pressure curve exhibited a "stair-step" pressure trace. This type of trace is a result of the intermittent contact in the center conductor occurring during recoil when the Microdot cable is in motion. Without an electrical short present, the signal to the charge amplifier will bleed off leading to a flat line, on a millisecond scale, until contact is re-established and the next level of charge is sensed leading to a trace that resembles a staircase. The problem is quickly rectified by replacing the problematic Microdot cable for the affected channel.

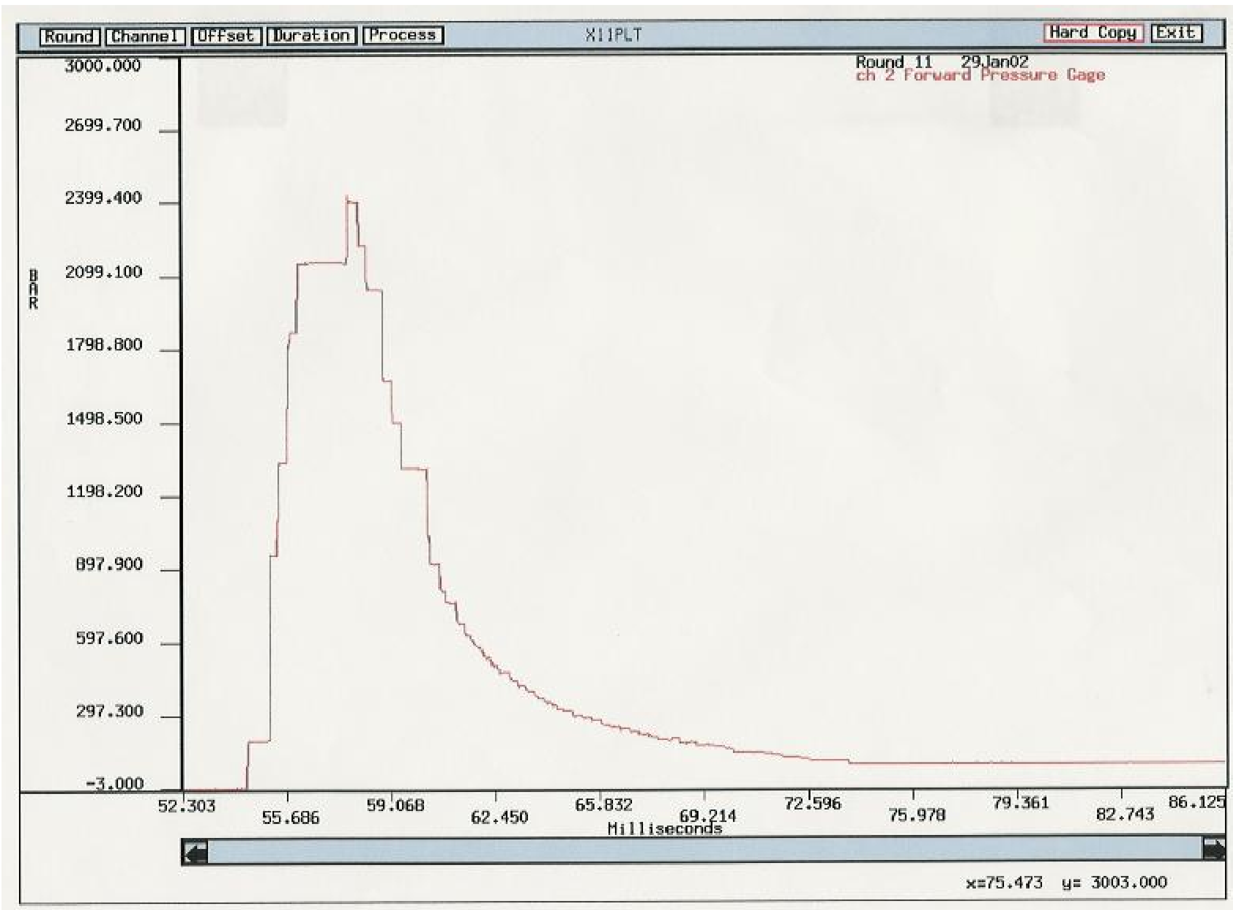


Figure 6. "Stair-step" trace characteristic of intermittent contact in the Microdot cable center conductor.

Case 3. Cartridge Case Misalignment or Improper Drilling.

Non-consumable cartridge cases require ports to be drilled through the case wall in order for the transducer sensing element to be exposed to the propellant gas pressure. Proper indexing of the cartridge case is essential for alignment with the transducer pressure port. Improper drilling or alignment can lead to errors in pressure traces ranging from lower peaks to cropped pressure traces to a complete absence of pressure data for the affected channel.

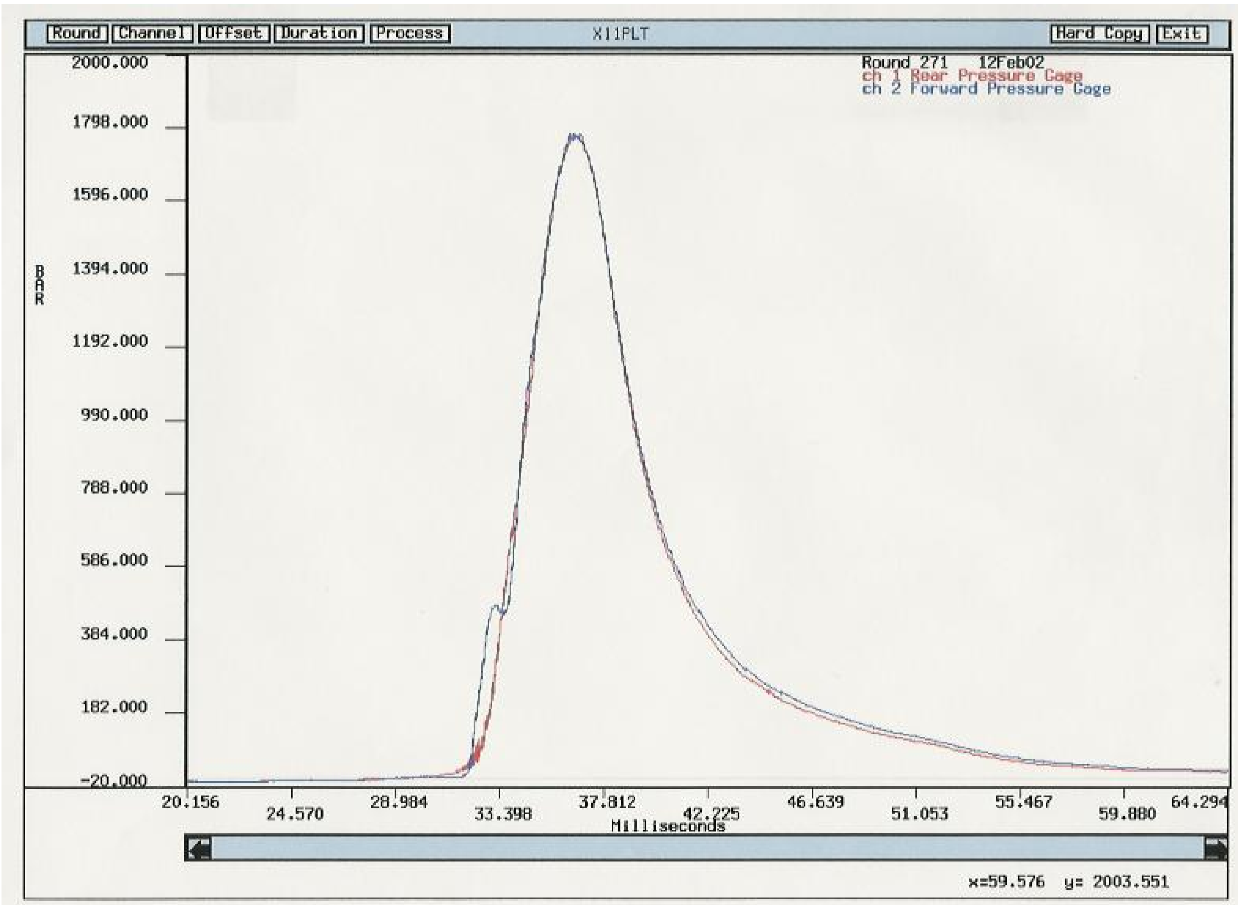


Figure 7. Small secondary peak created by pressure loss during blow-by at the pressure port until cartridge case sealing is restored by increasing pressure inside the case.

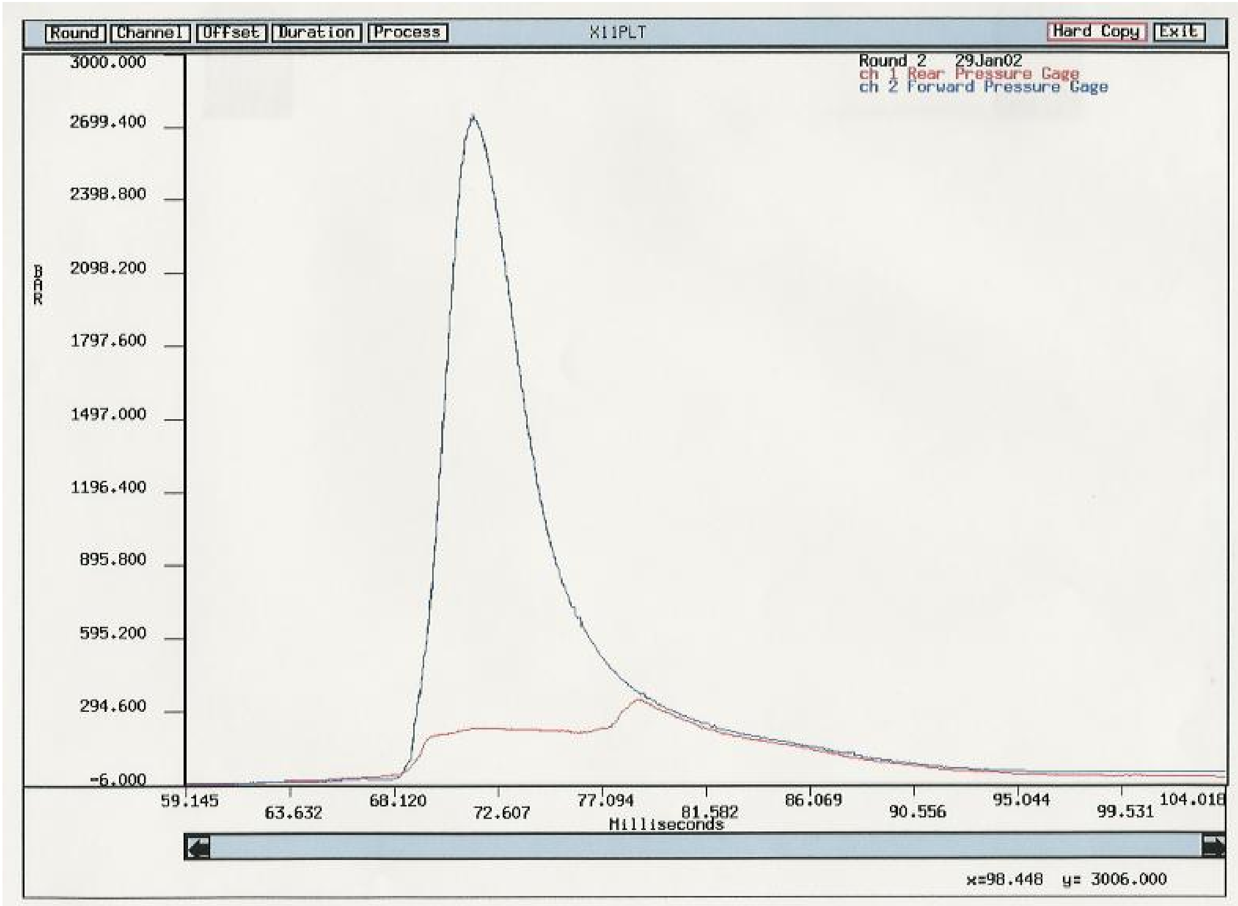


Figure 8. Truncated rear chamber pressure trace caused by misalignment of cartridge case with pressure port. The points where the curve deviate from and return to a normal profile are caused by the sealing and unsealing of the cartridge case against the chamber wall.


Figure 9. 90mm Cartridge case drilled for pressure ports. Note tarnishing of metal around pressure port locations and at the projectile crimp area caused by lack of case sealing and blow-by. This will eventually lead to erosion in the chamber wall leading to additional errors in pressure measurement.

Case 4. Absence of Cartridge Case Drilling.

In a developmental 105mm Cannon, a new design cartridge case featured plastic and metal construction and was intended to survive and be ejected from the gun after firing. Pressure ports were located at mid-chamber locations but did not have corresponding holes drilled in the plastic case. As a consequence, pressure built-up inside the cartridge case and punched holes through to the pressure port. This caused a small block of cartridge case material to impact against the sensing element of the transducer leading to a spike in the pressure trace on the affected channels. Repeated exposure to this type of event eventually led to destruction of the transducers.

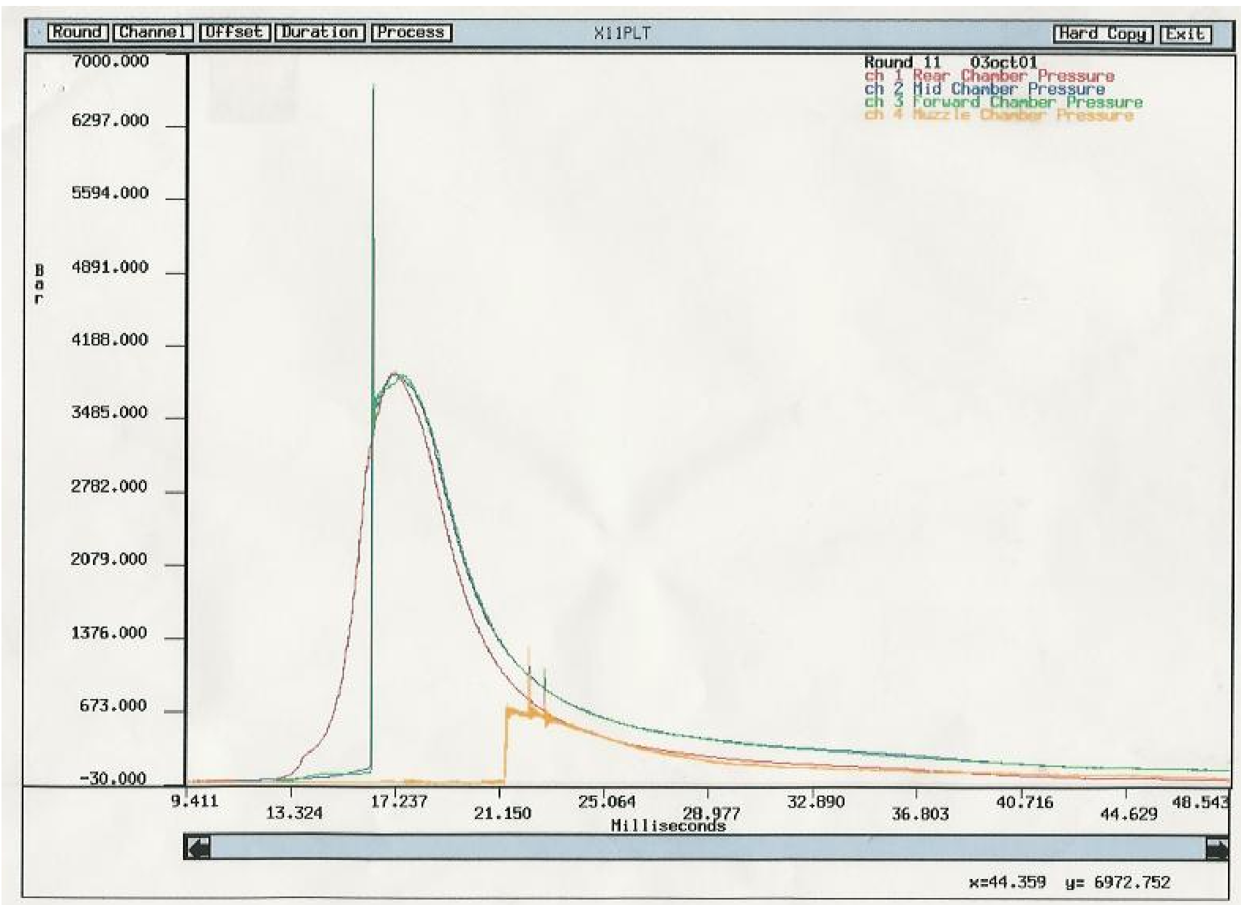


Figure 10. Spike affecting two channels of data caused by cartridge case material impacting on the pressure sensor.

Case 5. Electrical Artifacts in Pressure Traces.

During 120mm testing, drop outs were observed in the normal smooth curve of the pressure trace. Because the drop outs affected both channels of the data it was suspected that the cause was electrical in nature. Eventually a comparison was made to the line carrying the firing pulse and a corresponding post-ignition negative voltage spike was observed to coincide with the drop outs on the pressure curves. The problem was attributed to grounding with the weapon.

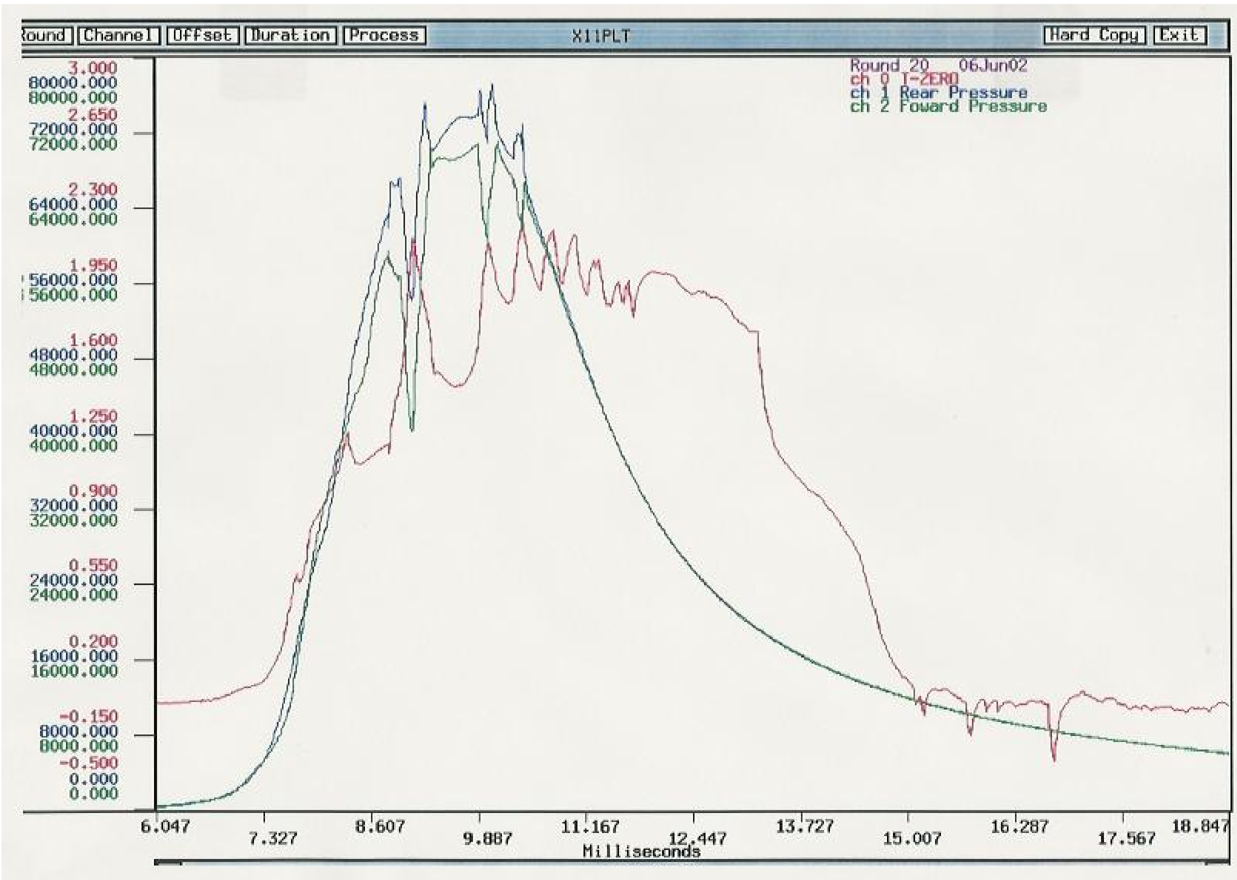


Figure 11. Simultaneous graph showing overlay of firing circuit voltage (channel 0) and forward (channel 2) and rear (channel 1) pressure channels.

Case 6. Software Induced Excessive Negative Differential Pressure.

During 120mm testing of a developmental round, a 1000 Bar negative differential pressure was observed. A differential pressure of this magnitude is cause for concern since it can lead to break up of propellant grains and detonation leading to physical damage to the cannon. The propellant had been recovered for re-use from previously manufactured tactical rounds; consequently propellant aging was a real concern. A review of instrumentation causes that might lead to a phase shift was undertaken by the ballistics technician. A capacitance meter was used to check differing levels of capacitance in the front and rear channels. Readings of 1995 and 1989 picoFarads were obtained; the difference between these two values was deemed too small to explain the phase shift. A Time Domain Reflectometer was used to check the condition of the cables leading out to the transducers. A graphic display of the cable condition and location of splices or connections revealed no cable problems. The use of this particular instrument can be very valuable in gauging the integrity of long lengths of cable for opens or shorts and may become a regular requirement for ballistics testing. Ultimately the ballistics technician identified parameter settings in the Ballistics Test Site software that could lead to a phase shift. Channels are setup either as a “Slave” or “Master” to establish a trigger order. Standard practice is to have one primary “Master” (typically firing circuit voltage) and a backup “Master” (typically the rear chamber pressure gage). When the threshold voltage is reached for either “Master” channel, data begins being recorded, and the “Slave” channel(s) begin recording at the moment of “Master” trigger. Without a “Master trigger”, the “Slave” channels will not record any data. On this particular occasion, each pressure channel was set as a “Master” with no corresponding “Slave”. The net result was that each pressure channel would trigger independently once its threshold voltage was reached. When the data was submitted to the plotting routine the time axis for each curve would be automatically be aligned to zero and a phase shift would be induced. Once the cause was identified, the parameters were re-set so that the forward channel became a “Slave” of the “Master” rear channel.

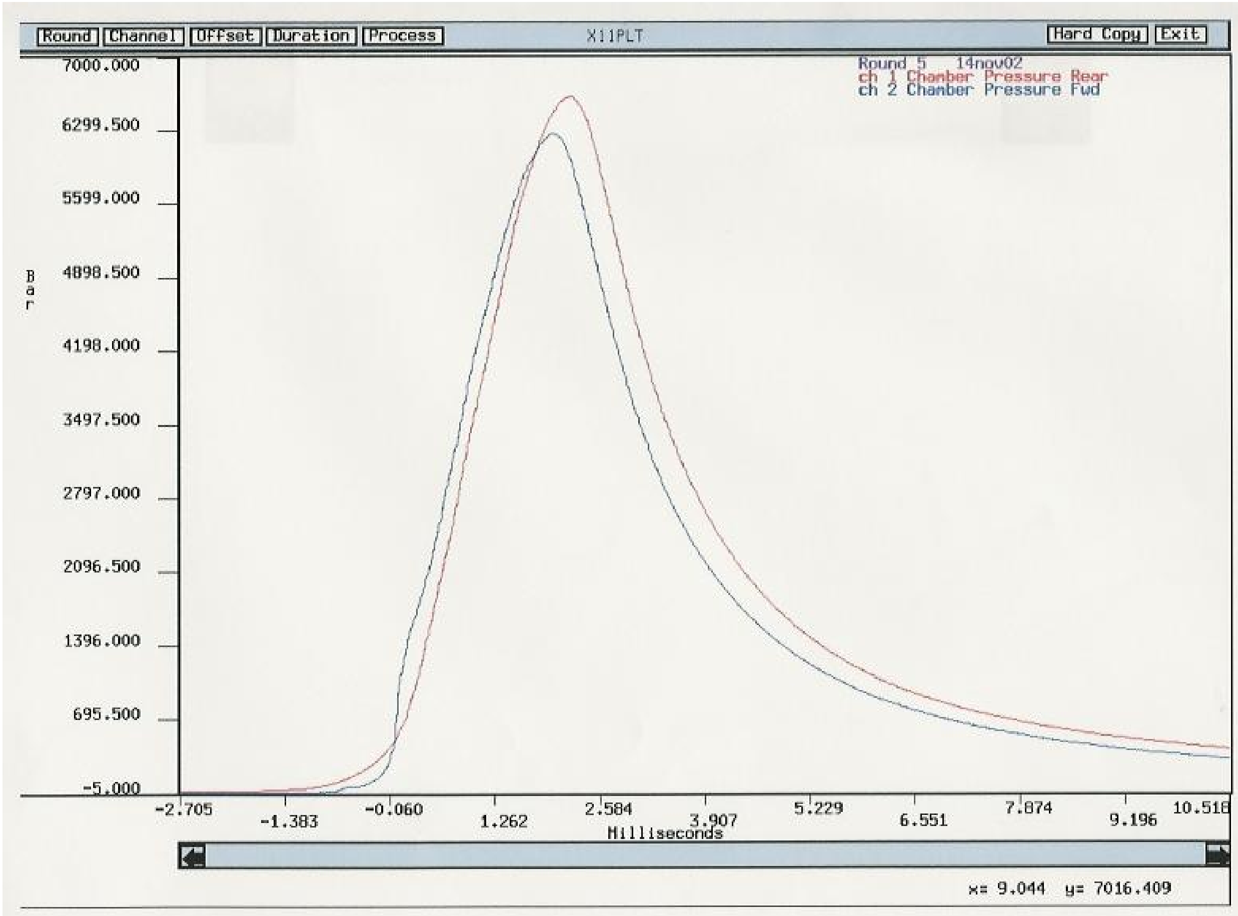


Figure 12. Phase shift leading to an apparent excessive negative differential pressure. A check of the Ballistics Software parameters revealed that each channel was acting independently as a "Master". Slaving the forward channel to the rear linked the previously separate events and eliminated the phase shift.

Case 7. Pressure Reversal Induced by Blow-by.

During the firing of a 175mm cannon recurring pressure reversals were seen in the pressure traces. The 175mm cannon employs a spindle to seal the rear of the chamber. The spindle is drilled to accept a Microdot cable and has two threaded holes for attaching an adaptor containing the pressure transducer. A Kistler Model 607C Pressure Transducer was installed into the adaptor. The adaptor was held in place on the front of the spindle by two ¼-28 Socket Head Cap Screws which were torqued in place by hand. A large full face copper seal was used to provide the pressure sealing between the adaptor and the cannon spindle. Physical examination of the spindle showed scorching and propellant residue behind where the adaptor pressure seal was located.

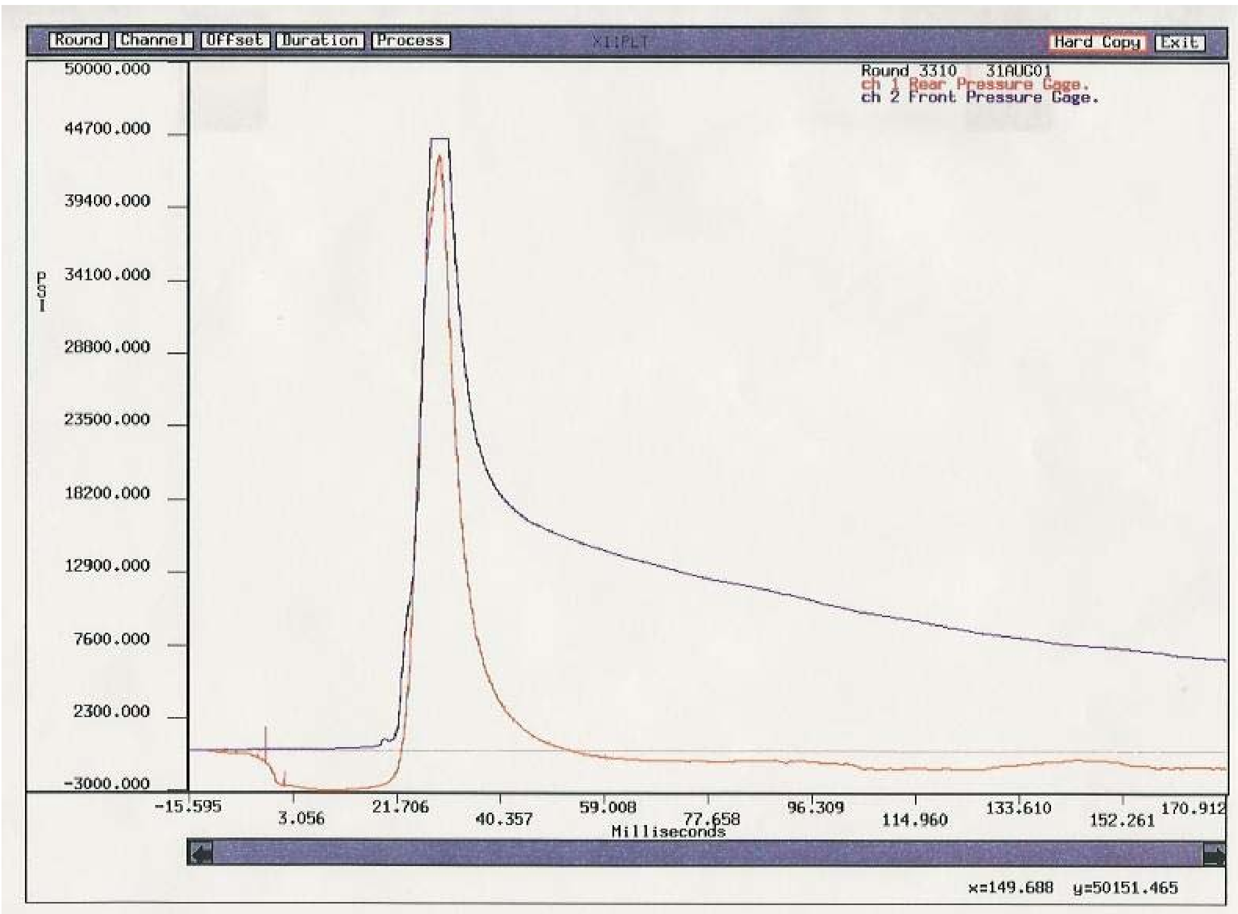


Figure 13. Lower than expected rear pressure caused by inadequate pressure sealing between the adaptor holding the pressure transducer and the spindle. Propellant gases were able to escape behind the transducer leading to a localized lower rear pressure. Note the “clipping” of the front channel – this is caused by setting too low a Peak Pressure parameter leading to an out-of-measurement-range condition for the data acquisition software.

Figure 14. Assembly of pressure transducer adaptor to 175mm spindle. The adaptor is held in place by hand tightening two ¼-28 socket head cap screws. Hand tight torque on these two screws is inadequate to compress the full face pressure seal behind the adaptor leading to propellant leakage behind the adaptor and lower than expected rear chamber pressure.

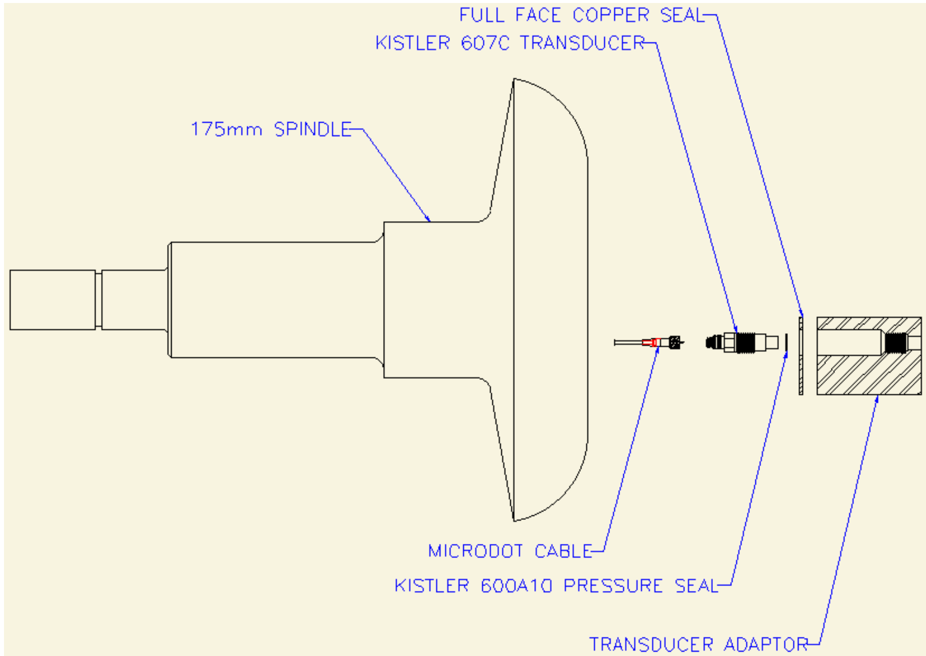
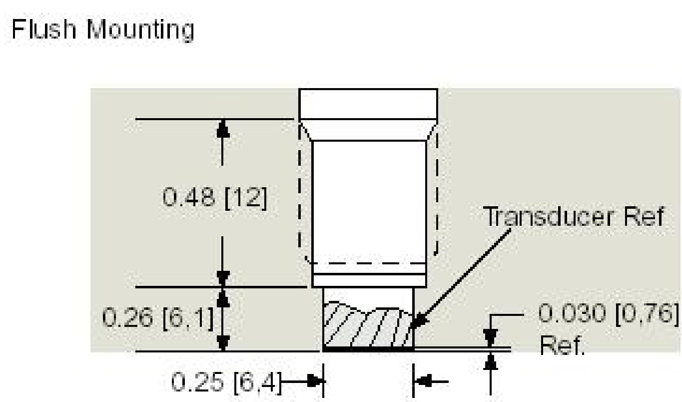
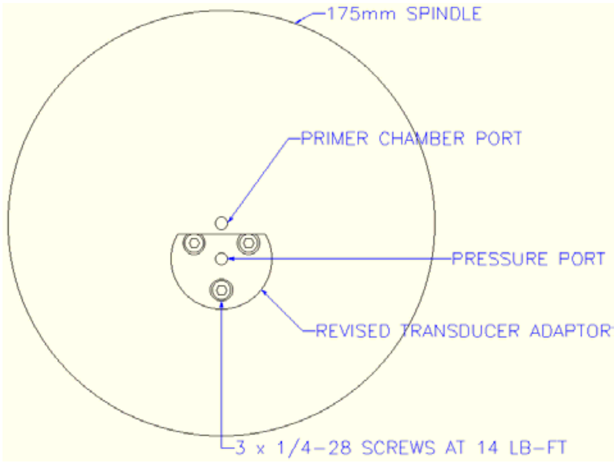


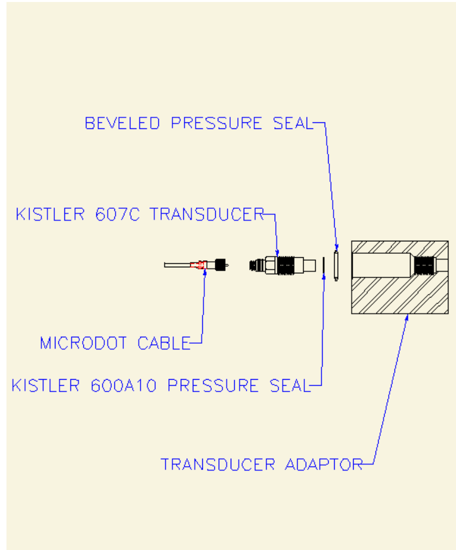
Figure 15. General arrangement of transducer adaptor, pressure seals, and transducer for measuring rear pressure in 175mm cannon. Not shown are the two ¼-28 socket head cap screws hand tightened to assemble the adaptor to the spindle.

The transducer adaptor design can be improved by machining existing hardware or by fabrication of new adaptor body (preferred). First, the full face copper seal needs to be reduced in size to permit crushing and intimate contact following application of screw torque. This can be done by confining sealing to the diameter immediately around the transducer cavity. The seal itself would then become approximately Ø.625 inch. Matching 150° beveled surfaces would then be machined into the seal and corresponding sealing surfaces of the spindle and adaptor providing maximum compression of the seal during installation and especially during cannon firing. Specifying a 14 lb-ft torque level for ¼-28 hardened alloy steel socket head cap screws would be required. Improved compression of the pressure seal would be obtained by adding a third screw to the adaptor assembly; the screws would be equally spaced for proper distribution of the clamping force during torque application.



Figures 16a and 16b. Kistler Model 607 transducer and flush mount pressure port.





Figures 17a and 17b. Slightly revised transducer adaptor design with ¼-28 hardened alloy screws equally spaced and torqued to 14 lb-ft. A beveled copper pressure seal replaces the full face seal previously used. The higher clamping force from the three screws and the smaller seal surface area will assure compression and contact between the sealing surfaces of the spindle and adaptor.

1.3 CONCLUSIONS

The majority of chamber pressure measurements conducted at Aberdeen Test Center are accomplished with little or no difficulty at all. On rare occasions abnormalities appear that frustrate the ballistics technician and the pressure measurement customer. Through the application of good technical know-how and deductive reasoning these abnormalities can be explained as they occur or mitigated before they occur. The explanations presented for these specific cases may be applied to other instances of pressure measurement abnormalities. Certainly there will be other occurrences that are not readily explained by the examples contained herein but it is expected that they can and will be addressed in future documents.